Neutron Background to Atmospheric Neutrino Analyses

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- Neutrons produced from interactions of cosmic muons in rock are potential background in atmospheric neutrino event samples
  Particularly if muon not seen in detector
- Try to estimate rate of neutrons incident on MINOS FD:
  (a) from Soudan 2 data
  (b) from MC calculations performed by other expts
  (c) from my GEANT4 simulation

Neutrons in Soudan 2

- Soudan 2 observed 74 neutrons/year (rock + qs-rock) with $E_{\rm vis} >$300 MeV in fiducial volume (PRD68 (2003) 113004)
- Neutron attenuation length $\sim$ 80 cm; fiducial volume 20 cm from edge $\Rightarrow$ 95 n/y incident (assuming normal incidence)
- Top area of MINOS FD $\sim$ 2$\times$ Soudan 2
  $\Rightarrow$ 200 n/y incident on MINOS with $E_{\rm vis} >$ 300 MeV
- This is **LOWER LIMIT** on neutron flux with $E_{\rm n} >$ 300 MeV:
  Attenuation actually greater because not generally at normal incidence
  Soudan 2 efficiency for neutrons unknown
  $E_{\rm vis} >$300 MeV corresponds to neutron energy $E_{\rm n} \geq$????

MC Calculations from Other Experiments

- Neutrons form significant background for dark matter experiments: several MC estimates of neutron background exist from these labs
- Use their quoted rates of neutrons/muon and neutron energy spectra to estimate rate for $E_{\rm n} > 300$ MeV, assuming 100k muons $\equiv$ 36h
- Values estimated from three calculations:

  Canfranc: 11000 n/y

  Gran Sasso: 30000 n/y

  Boulby: 14000 n/y

- These probably UPPER LIMITS (but large uncertainties)

  These labs deeper than Soudan $\Rightarrow$ harder muon spectrum $\Rightarrow$ higher muon-nuclear interaction cross-section $\Rightarrow$ more neutrons
- Clearly orders of magnitude uncertainties in rate

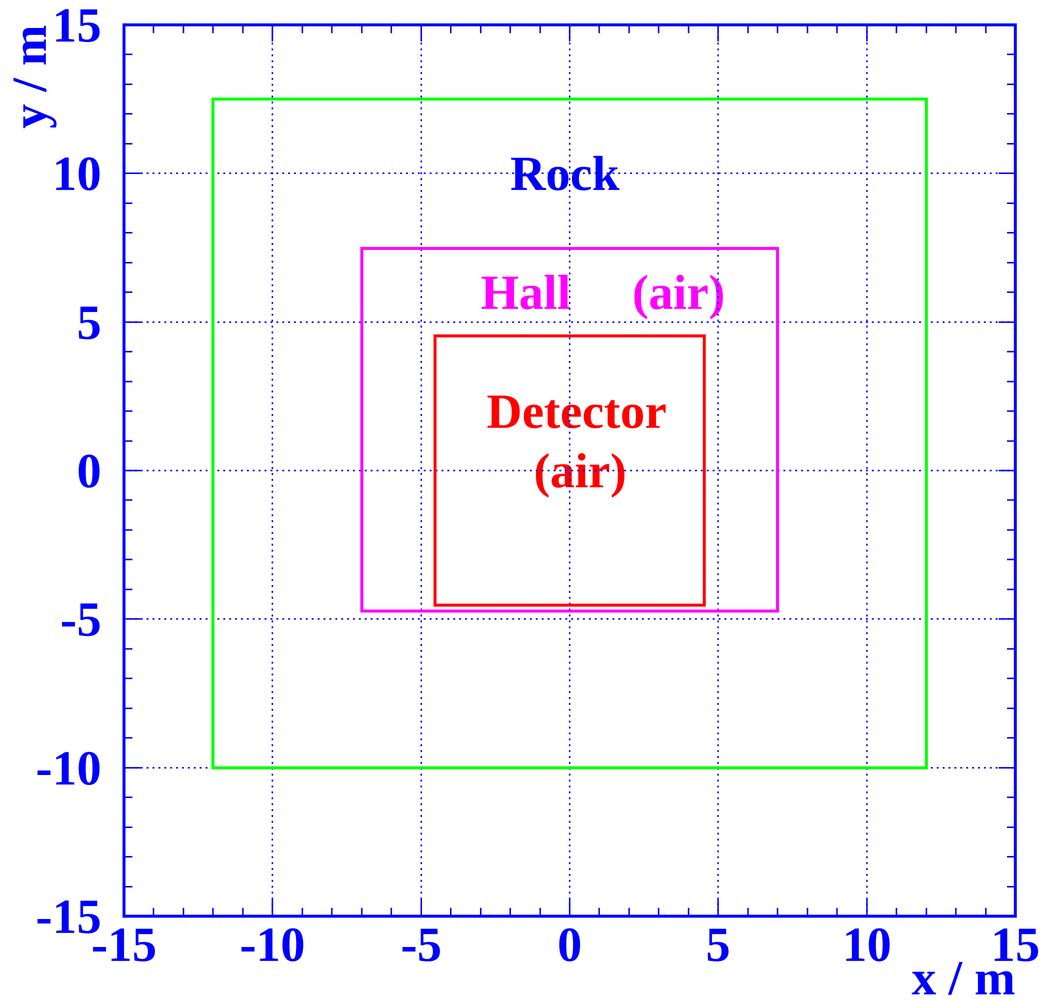
GEANT4 Simulation

- Very simple geometry:
- 'Detector' = box of air $9.06 \times 9.06 \times 34.0$m
- Surround by

  HALL (air)

  ROCK (concrete: A=22.9 Z=11.4 ρ=2.5g/cc)

  Dimensions and materials as in GMINOS

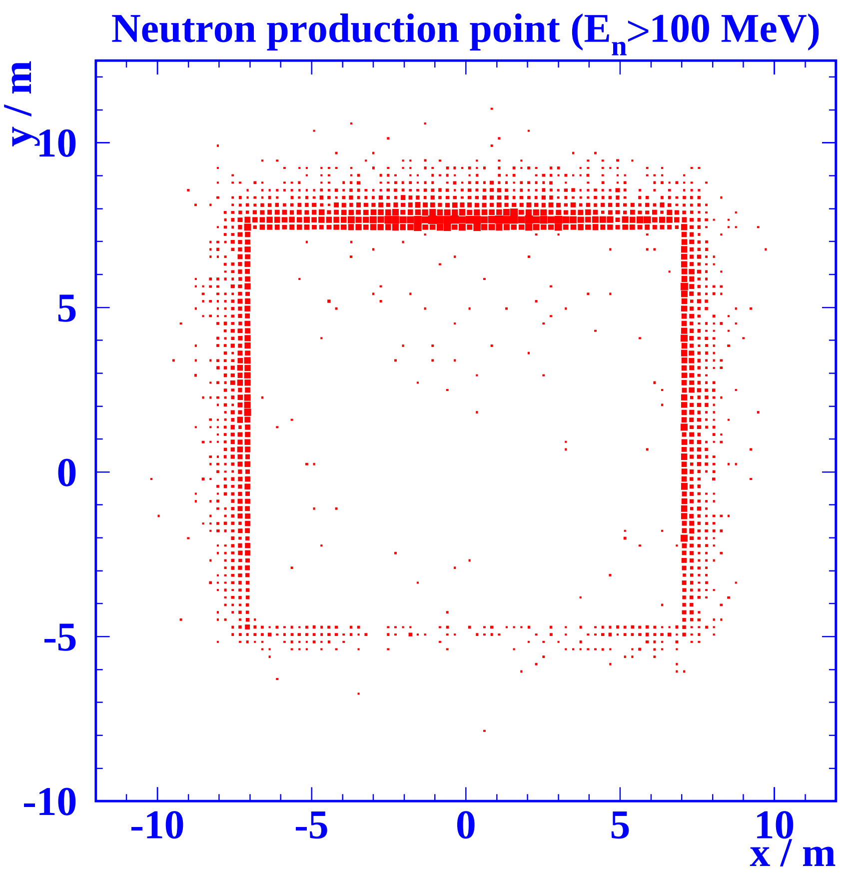


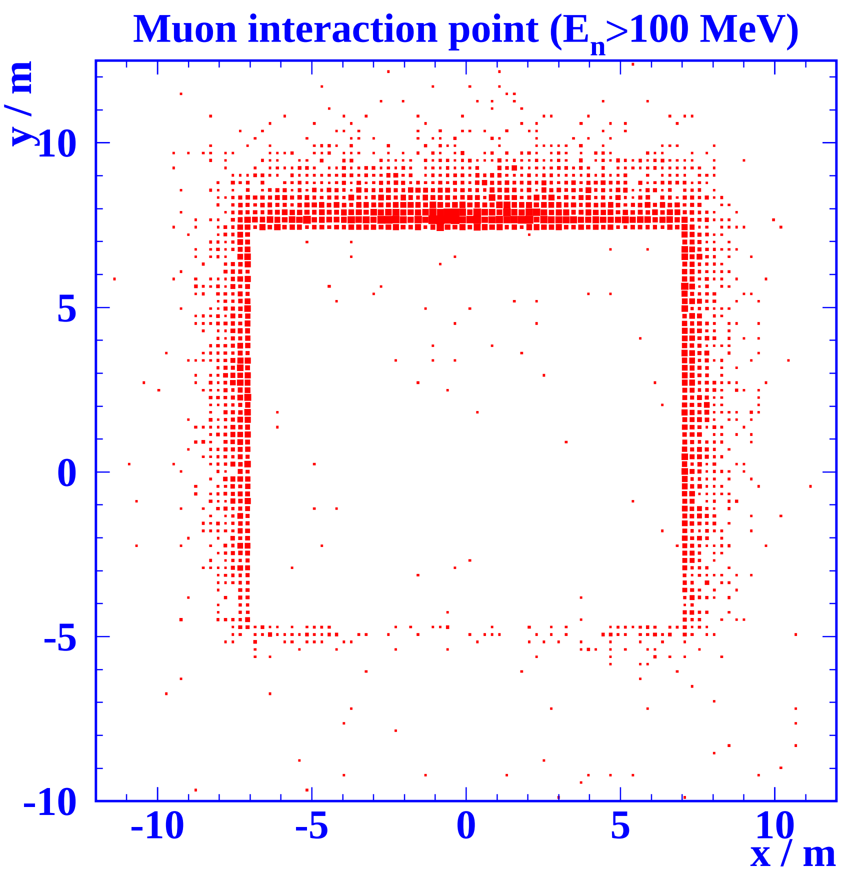
GEANT4 Simulation

- Cosmic muon flux as in atmospheric ν background studies
- Take muons incident on box 5m from detector, and extrapolate back so they traverse (at least) 5m rock
- Physics processes as in example N04 (usual em, hadronic int., decays etc.) with addition of muon nuclear interactions
- Track muon until reaches detector, decays or leaves 'world'. If there has been a muon nuclear interaction, continue tracking and save all particles entering detector volume; otherwise kill event
- Save ONLY events with at least one neutron entering detector; for these, output all particles which enter detector

Muon Interaction Vertex

- High energy neutrons reaching detector almost all produced within last $\sim$2 m of rock



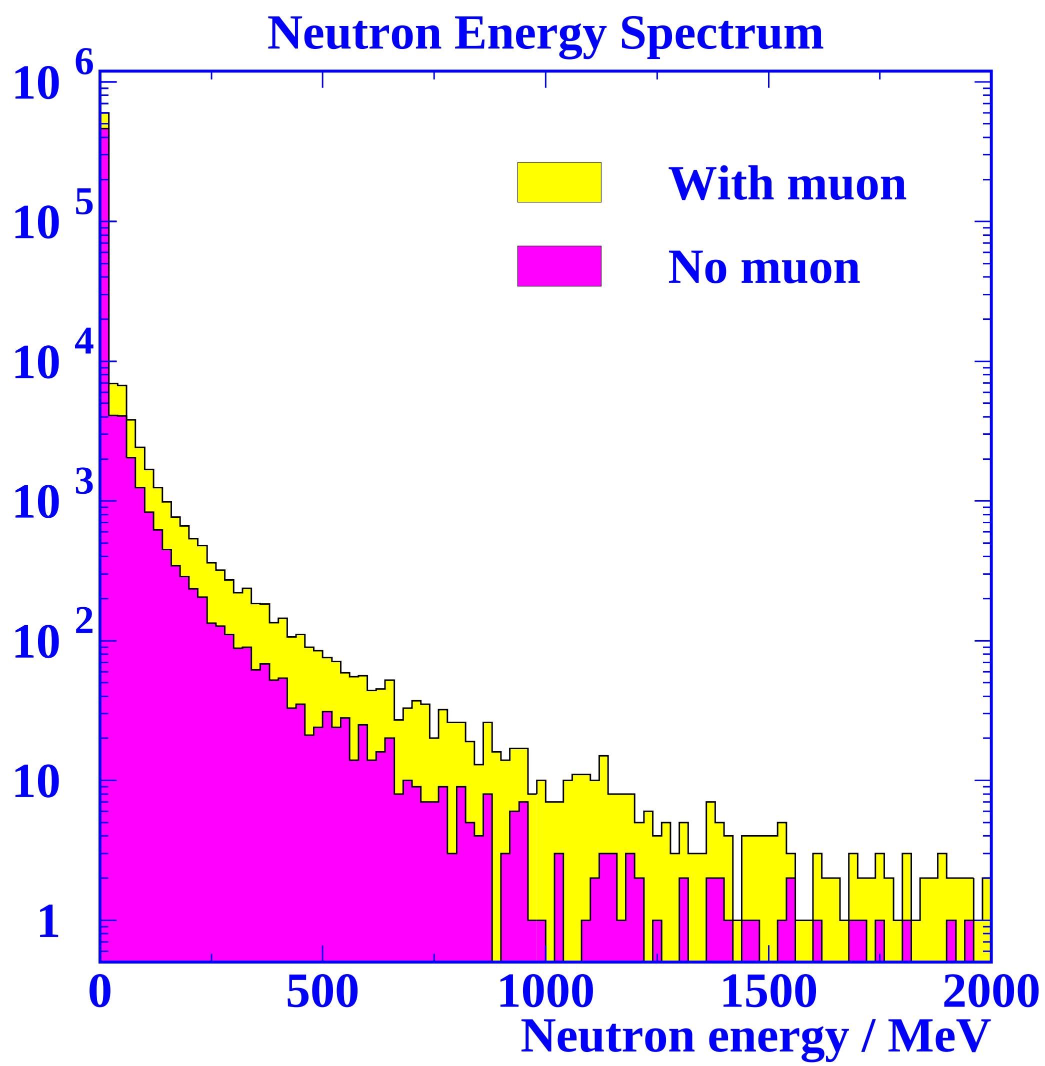


Results

- Results based on 30M muons ($\equiv$ 156 days)
- Approx 0.9% give $\geq$ 1 neutron incident on detector volume
  In these, mean number of particles hitting detector = 14.4$\pm$0.2, but some events have 10000 or more (mostly low energy photons)
- Number of neutrons per muon with $E_{\rm n} >$20 MeV = 29822/30M = 0.001
- How does this compare with other simulations? Comparison difficult as I only save events with neutron incident on detector
- hep-ex/0403009 (Canfranc) quote mean number of neutrons per muon with $E_{\rm n} >$20 MeV = 0.007
- But number of neutrons $\sim E_{\mu}^{0.75} \Rightarrow$ expect Soudan/Canfranc $\sim$ 0.5
- Only $\sim$30% of generated muons point to my detector volume $\rightarrow$ multiply my rate by $\sim$ 3
- Hence rates roughly consistent

Neutron Energy Spectrum

- 19% of neutron events have muon incident on the detector
- These tend to be higher energy neutrons
- With muon: $< E_{\rm n} >$ = 14.8 MeV
- No muon: $< E_{\rm n} >$ = 3.7 MeV



Neutron Energy Spectrum

Neutron Energy Spectrum

- Neutron energy spectrum well-described by sum of two exponentials for $E_{\mathrm{n}} > 100$ MeV:

$$\frac{\mathrm{d}N}{\mathrm{d}x} = a\mathrm{e}^{-E/\alpha} + b\mathrm{e}^{-E/\beta}$$

with α = 76$\pm$6 MeV and β = 279$\pm$21 MeV (for all events)

- c.f. hep-ex0403009 suggests single exponential with range-dependent exponent

$$\frac{\mathrm{d}N}{\mathrm{d}x} \sim a\mathrm{e}^{-E/\alpha}$$

with α = 77 MeV for $E <$200 MeV and α = 250 MeV for $E >$200 MeV

- Single exponential does not fit my distribution, but exponents of double exponential similar

Neutron Angular Distributions

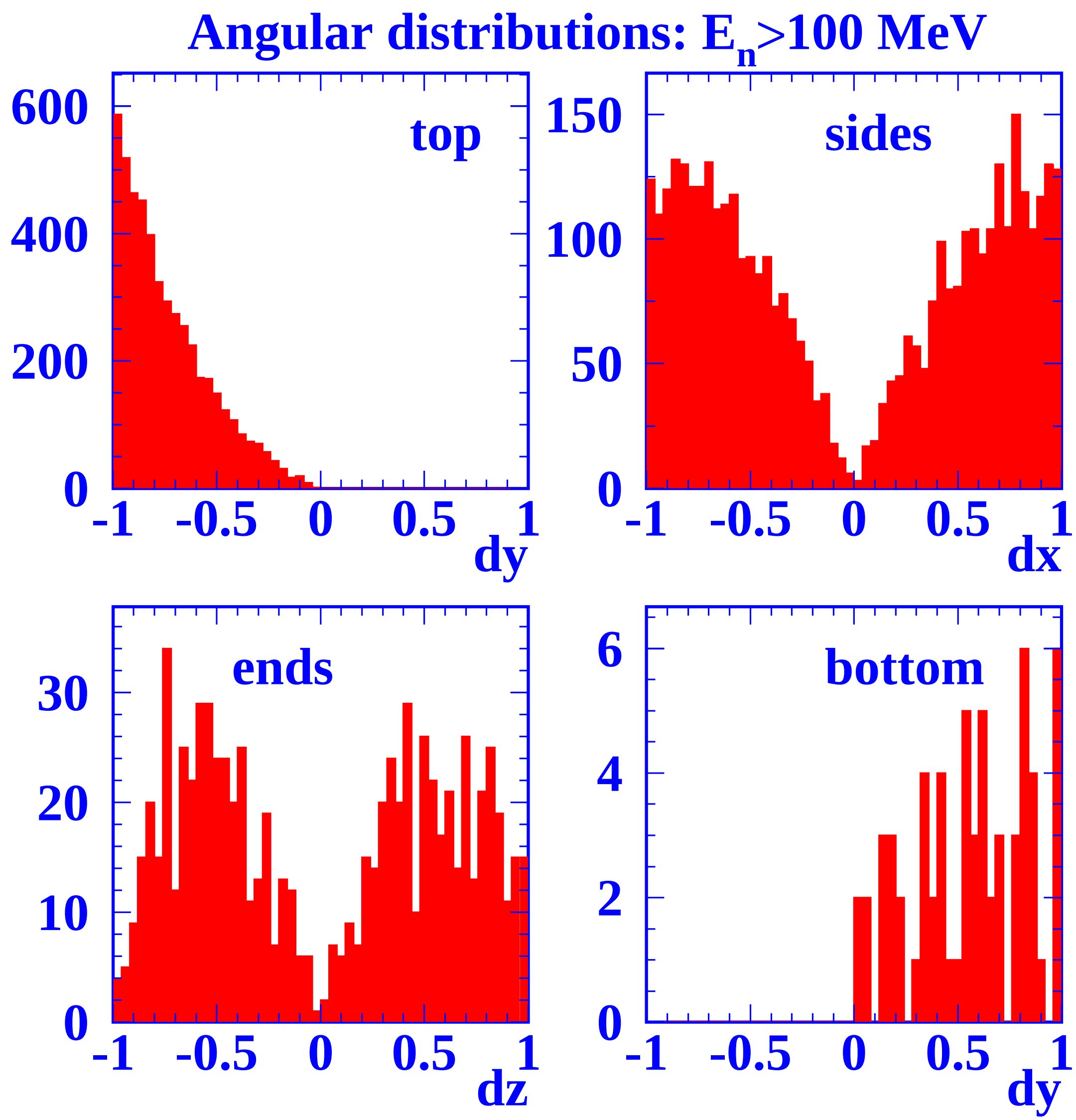
- High energy neutrons tend to enter detector at top
- For $E_{\rm n} >$100 MeV:

  49% enter top surface

  42% enter sides

  8% enter ends

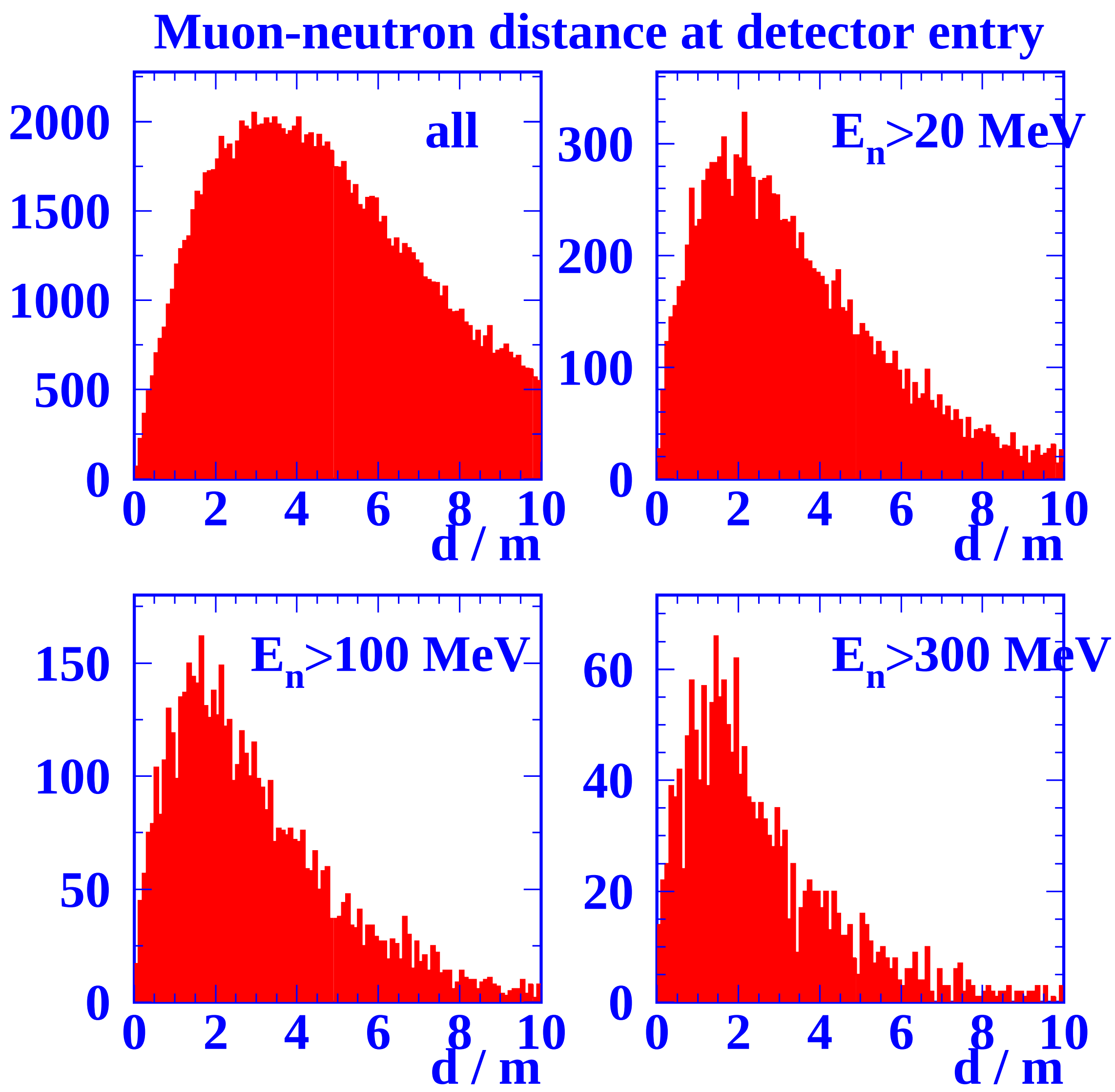
  1% enter bottom



Muon-neutron Separation

- Separation between muon and neutron at detector entry typically metres, decreasing with energy
- For $E_{\mathrm{n}} > 100$ MeV (300 MeV), approx. 18% (13%) of neutrons enter detector more than 5 m from muon

  $\Rightarrow$ maybe use bigger box



Neutron Rate?

- Simulation gives following rates per year for neutrons incident on detector:

	All	No muon
$E_{\rm n} >$20 MeV	69800$\pm$400	36600$\pm$300
$E_{\rm n} >$100 MeV	23300$\pm$200	9800$\pm$150
$E_{\rm n} >$300 MeV	6200$\pm$100	2000$\pm$70

- Higher than rates estimated from Soudan 2 data, lower than estimates from other simulations

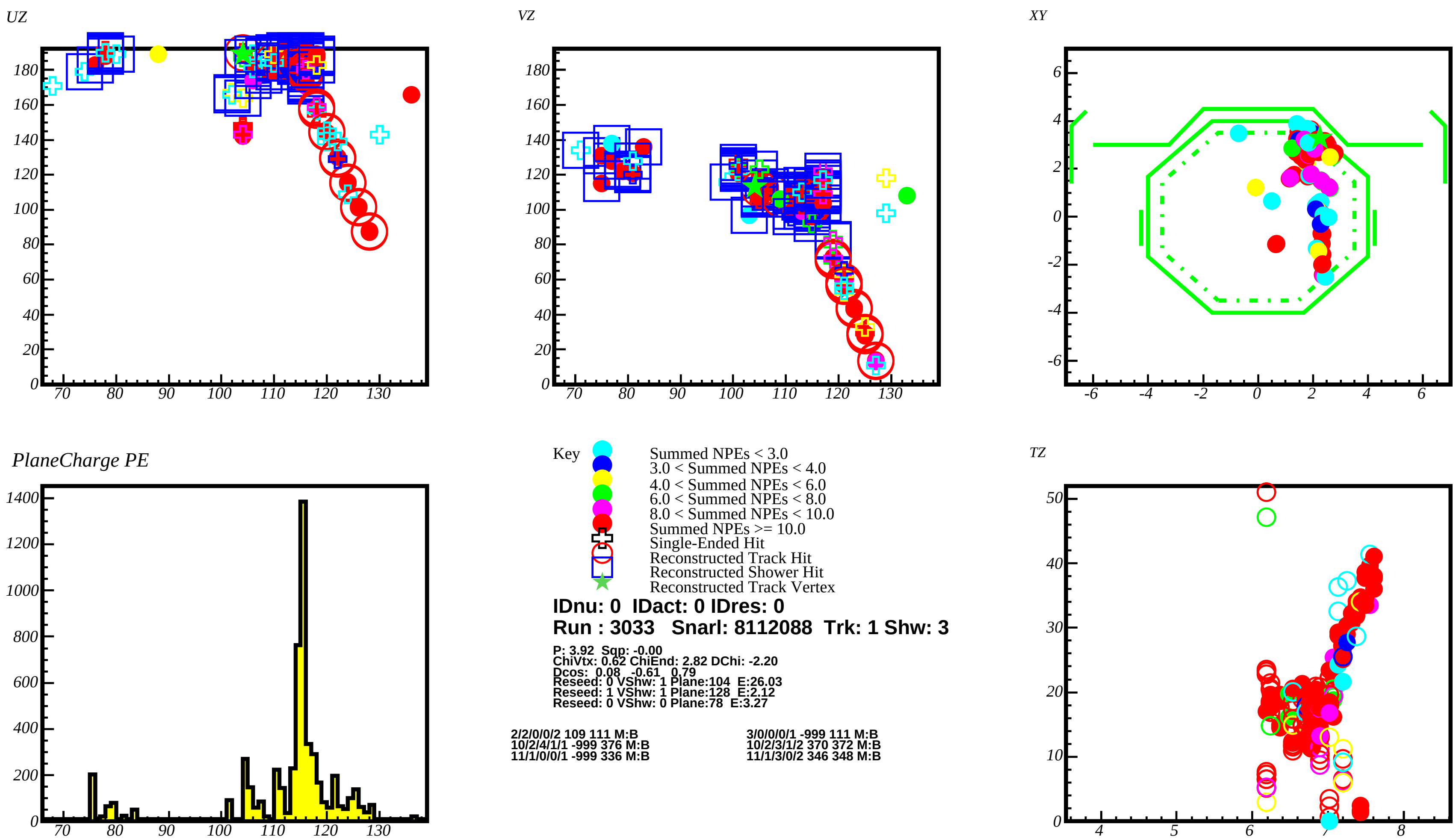
- Next step: feed output of G4 simulation into GMINOS

  7583 events with a neutron $>$100 MeV processed through gminos

  Reconstructed by Andy Blake $\Rightarrow$ no event passes event selection

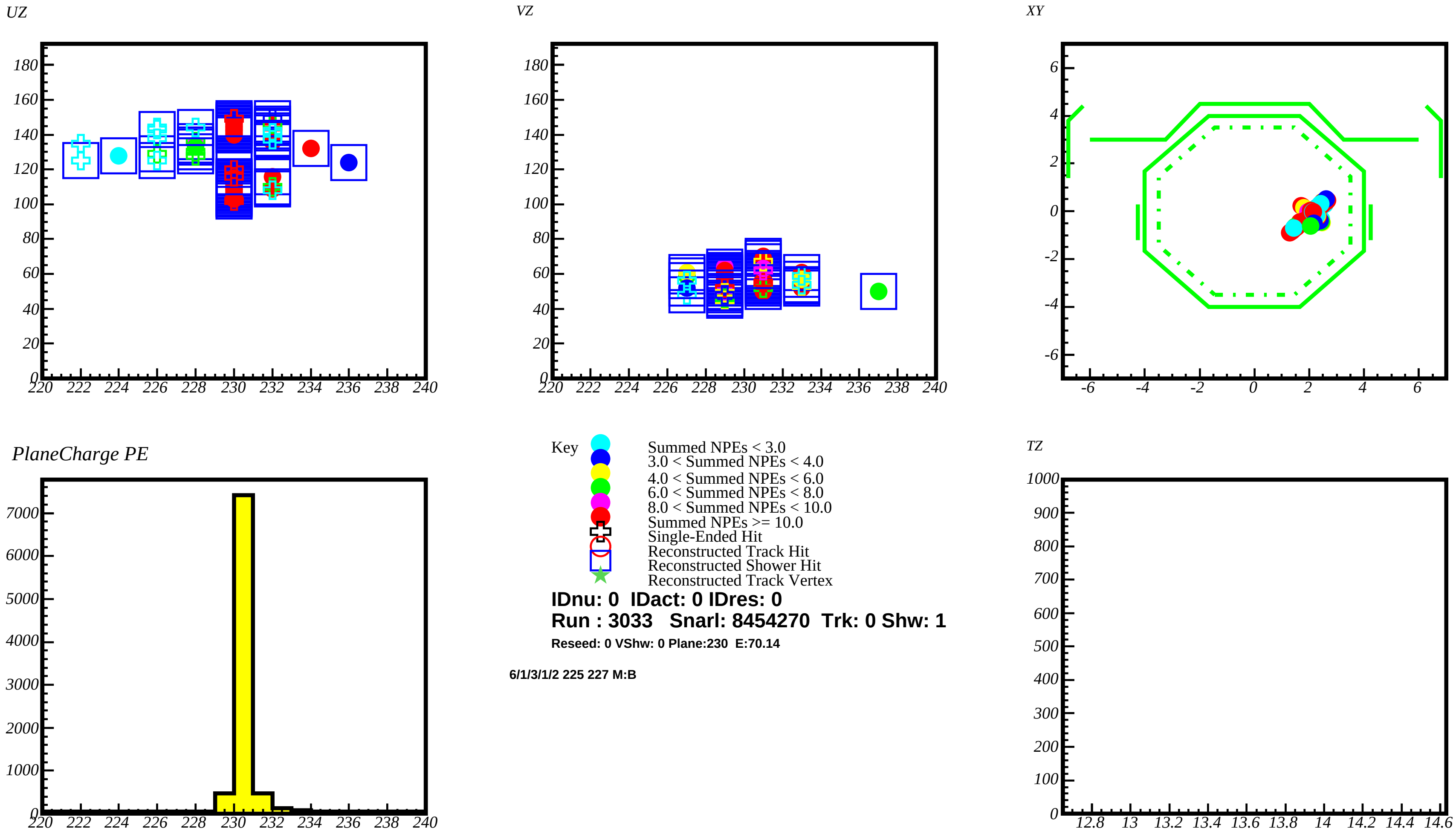
Typical Event...

312 GeV μ^- interacts $\sim$30 cm from rock-hall interface producing high multiplicity shower: 423 particles incident on detector



Another Typical Event...

82 GeV μ^- interacts few cm from rock-hall interface; 13 partcles hit detector



Summary

- Have set up simple GEANT4 job to study neutron background to atmospheric neutrino analyses from cosmic muon interactions in rock
- First results indicate rates of about 6000 (2000) neutrons per year with $E_{\mathrm{n}} >$300 MeV including (excluding) those with muon incident on detector
- These rates are higher than estimates using Soudan 2 data, but lower than very rough estimates derived by extrapolating results of MC simulations performed for other experiments
- Output of GEANT4 simulation can be input to GMINOS and reconstructed to study selection efficiency
- Future: higher statistics, modify starting box, rock thickness (composition?) etc.